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Increased heat fluxes near a forest edge

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With 11 Figures

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Summary

Observations of sensible and latent heat flux above forest downwind of a forest edge show these fluxes to be larger than the available energy over the forest. The enhancement averages to 56 W m^{-2}, or 16% of the net radiation, at fetches less than 400 m, equivalent to fetch to height ratios less than 15. The enhancement of turbulent energy fluxes is explained by advection and increases with the difference in temperature and humidity of the air over the upwind area as compared to the forest. The relatively high temperature and humidity of the upwind air are not caused by high surface heat fluxes, but are explained by the relatively low aerodynamic roughness of the upwind surface. Although the heat fluxes over forest are enhanced, the momentum fluxes are almost adjusted to the underlying forest. The different behaviour of heat and momentum fluxes is explained by absorption of momentum by pressure gradients near the forest edge. It is concluded that fetch requirements to obtain accurate surface fluxes from atmospheric observations need to be more stringent for scalar fluxes as compared to momentum fluxes.

1. Introduction

The interaction between atmosphere and vegetation influences the weather and ultimately the climate patterns. This exchange almost never reaches an equilibrium, but is constantly adapting to changing boundary conditions. For the improvement of input parameterisation of Global Circulation Models, it is important to establish average exchange parameters at the grid size of these models. Simple aggregation rules have been provided, e.g. at the Tucson Aggregation Workshop (Michaud and Shuttleworth, 1997). The validity of these rules is questionable when large variations in vegetation height occur (Klaassen and Claussen, 1995). For instance, the roughness of a patchy landscape is not always a weighed average of the elements, but might even exceed the roughness of the roughest element (Bottema et al., 1998). The large roughness is attributed to additional momentum absorption at changes in vegetation height, in particular forest edges and tree lines (De Jong et al., 1999).

In order to improve the aggregation rules, it is desirable to understand the exchange processes near surface transitions. Another reason to study exchange processes near forest edges is that most forests are too small to fullfil the fetch requirements for observations in undisturbed, homogeneous flow (Wieringa, 1993). As a consequence of limited fetch, the atmospheric flux might deviate from the source strength of the underlying surface. An analysis of the difference between atmospheric and surface fluxes near a forest edge might improve the estimation of fluxes from patchy forests from atmospheric measurements.

Nearly all measurements of atmospheric fluxes near a forest edge have been restricted to the fluxes of momentum (Gash, 1986; Kruijt, 1994; Gardiner et al., 1995; Irvine et al., 1997; van Breugel et al., 1999a; Flesch and Wilson, 1999). It is the aim of this study to extend the forest edge research to energy fluxes. The intention is to compare the atmospheric heat fluxes with the surface values. A complication arises as the heat fluxes of the forest surface are difficult to measure directly. However, the sum of sensible and latent surface fluxes can be estimated rather well from the local energy balance. The study therefore focusses on processes that may cause an imbalance of the heat fluxes downwind of a forest edge.

2. Theory

2.1 Conservation of energy

The internal energy of an air parcel c ($\mathrm{J\,m^{-3}}$) is defined as the sum of the sensible and latent energy:

$$c = \rho c_p \theta + \lambda \rho_v \tag{1}$$

where ρ is the air density ($\mathrm{kg\,m^{-3}}$), ρ_v the water vapour density ($\mathrm{kg\,m^{-3}}$), c_p the specific heat of air at constant pressure ($\mathrm{J\,kg^{-1}\,K^{-1}}$), λ the latent heat of vaporization ($\mathrm{J\,kg^{-1}}$) and θ the potential temperature (K). Conservation of energy in an air volume implies that (Stull, 1988):

$$\underset{\mathbf{T1}}{\frac{\partial \bar{c}}{\partial t}} + \underset{\mathbf{T2}}{\frac{\partial \overline{u'c'}}{\partial x}} + \underset{\mathbf{T3}}{\bar{u}\frac{\partial \bar{c}}{\partial x}} + \underset{\mathbf{T4}}{\bar{c}\frac{\partial \bar{u}}{\partial x}} + \underset{\mathbf{T5}}{\frac{\partial \overline{w'c'}}{\partial z}} + \underset{\mathbf{T6}}{\bar{w}\frac{\partial \bar{c}}{\partial z}} + \underset{\mathbf{T7}}{\bar{c}\frac{\partial \bar{w}}{\partial z}} = \underset{\mathbf{T8}}{S_c} \tag{2}$$

where **T1** represents the temporal storage, **T2** the horizontal flux divergence, **T3** the horizontal advection, **T4** the accumulation by horizontal flow divergency, **T5** the vertical flux divergence, **T6** the vertical advection, **T7** the accumulation by vertical flow divergence and **T8** the source term.

Equation (7) is simplified by assuming incompressible flow, or:

$$\frac{\partial \bar{u}}{\partial x} = -\frac{\partial \bar{w}}{\partial z} \tag{3}$$

and thus: $\mathbf{T4} + \mathbf{T7} = 0$.

The average influence of **T1** on the energy budget is estimated roughly for daytime conditions using: $z_m = 30\,\mathrm{m}$ and $\partial\theta/\partial t = 1\,\mathrm{K\,hr^{-1}}$, resulting in $\mathbf{T1} = \rho z_m c_p \partial\theta/\partial t = 10\,\mathrm{W\,m^{-2}}$. The influence of **T1** is neglected in the study as its mean influence is within the accuracy of the flux measurements. Moreover, this study focusses on the sensitivity of the energy balance versus fetch and **T1** is expected to be hardly sensitive to wind direction or fetch.

It is difficult to determine the influence of **T2** as $\overline{u'c'}$ is seldomly measured. An estimate can be made by assuming that $\overline{u'c'}$ is a passive quantity, originating from the correlations of $\overline{w'c'}$ and $\overline{u'u'}$. Then, $\overline{u'c'}$, and $\overline{w'c'}$ will have the same order of magnitude. As the vertical gradient in $\overline{w'c'}$ is concentrated to the internal boundary layer height and the horizontal gradient in $\overline{u'c'}$ is spread over the much larger fetch in the internal boundary layer to the forest edge, it is reasonable to assume that $\partial\overline{w'c'}/\partial x \ll \partial\overline{w'c'}/\partial z$, and thus $\partial\overline{u'c'}/\partial x \ll \partial\overline{w'c'}/\partial z$. So, **T2** will be neglected in this study, in agreement with Bink (1996) and Yi et al. (2000).

The assumptions of $\mathbf{T4} + \mathbf{T7} = 0$, $\mathbf{T1} = 0$ and $\mathbf{T2} = 0$ result in: $\mathbf{T5} - \mathbf{T8} = -\mathbf{T3} - \mathbf{T6}$, or, by integration from the ground surface up to the measurement location z_m:

$$(\overline{w'c'})_{z_m} - \int_0^{z_m} S_c dz = -\int_0^{z_m} \bar{u}\frac{\partial c}{\partial x} dz - \int_0^{z_m} \bar{w}\frac{\partial c}{\partial z} dz \tag{4}$$

The left hand side of Eq. (4) shows the difference between the turbulent energy flux at measurement location and the integrated energy source strength below that height. This difference is called the **energy imbalance** (*I*). The right hand side of Eq. (4) shows the vertically integrated advection of energy. So, Eq. (4) states that the energy imbalance is caused by advection of energy below measurement level. The integrated energy source strength is set equal to $(R_n - G)$, the difference between net radiation and soil heat flux, so neglecting chemical transfer by photosynthesis and the temporal storage term **T1**. Note that Eq. (4) states that the turbulent flux needs to be measured perpendicular to the mean flow and advection occurs in both horizontal and vertical direction.

3. Experimental arrangement

3.1 Site

The experiments were executed at the Bankenbosch forest and the bordering Fochteloërveen bog, see Fig. 1. The forest observations have been described by Dolman et al. (1998) and the bog observations by Nieveen et al. (1998). Some details of these experiments, that are of significance for the present study, are summarized below. The site is flat and situated in the northeast of the Netherlands near the village Veenhuizen (53E 01′ 21″ N, 6E 24′ 32″ W). The Bankenbosch forest consists of many patches with tree species such as Beech (*Fagus Sylvatica*), Douglas fir (*Pseudotsuga menziesii*), Summer oak (*Quercus robur*), Scotch pine (*Pinus Sylvestris*) and Japanese larch (*Larix Kaempferi*). The measurement tower is placed on a site of *Larix Kaempferi*, with an average tree height of 19.7 m, thinned to an average Leaf Area Index (LAI) of only 1.8. The minimum distance to the forest edge is 150 m in western direction. At eastern wind directions with a long fetch over forest, the roughness length of the forest patch is determinated as $z_0 = 2.1$ m for an estimated displacement height of 12.5 m. The albedo of the forest is 0.10 (van Breugel et al., 1999a).

The bog is dominated by Purple moor-grass (*Molinia Caerulea*), but surface cover also consists of Cotton-grass (*Eriophorum vaginatum*), Heather (*Calluna vulgaris*) and Cross-leaved Heath (*Erica tetralix*). The z_0 of the bog is on average 0.05 m, and the albedo 0.16 (Nieveen et al., 1998). The LAI of the vegetation varies during the growing season between 0.3 and 1.7, and is approximately 0.8 during the period of this analysis. The data have been collected between 1 June and 1 October 1995.

3.2 Instrumentation

The turbulent energy flux is the sum of sensible and latent heat fluxes above the forest and is measured at 27 m height with an eddy correlation system on top of a vertical boom, consisting of a 3D sonic anemometer (Gill Instruments, Solent 1012R2), a fast response air thermometer (Omega 0.002″ thermocouple) and a fast response hygrometer (Campbell, Krypton KH20). The eddy correlation system operated with a sampling rate of 20 Hz, after which data were processed. The processing included coordinate rotation for a non-zero mean vertical wind velocity, using running average filtering with a time constant of 200 s. Half hour averages and covariances were stored. Net radiation is calculated from the measured upward and downward longwave (Kipp&Zonen CG1) and shortwave radiation (Kipp&Zonen CM21). The internal energy of the air is calculated from Vaisala HMP35A temperature and humidity sensors. The radiation and internal energy components were measured at a sampling rate of 0.05 Hz, and were also

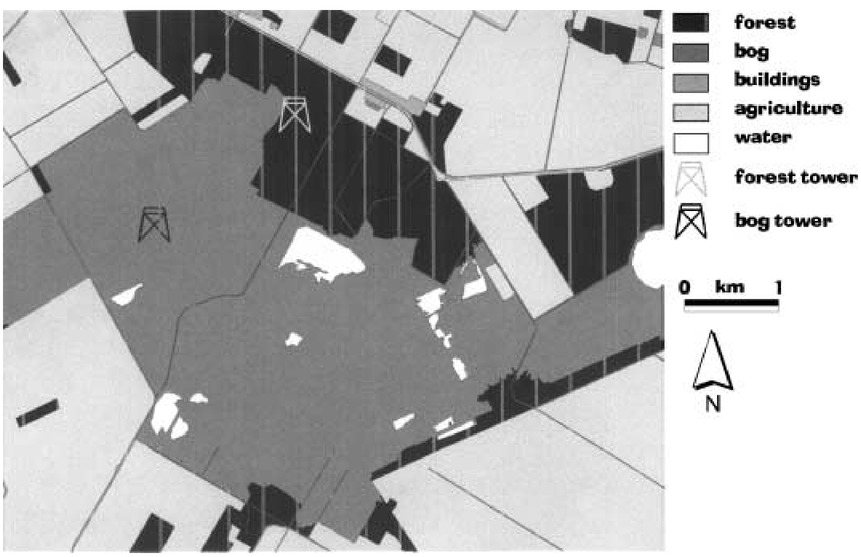


Fig. 1. Map of the measurement sites within the forest and surroundings. An arrow directing north is denoted in the legend

averaged over half an hour. The half hourly soil heat flux was obtained by three Hukseflux SH1 flux rings, and one TPD-TNO WS31 flux plate in the soil (Van Loon et al., 1998). Sensible and latent heat fluxes at the nearby bog were measured with a Gill 3D-sonic anemometer at a height of 8 m, combined with a fast response thermometer and a LiCor CO_2/H_2O gas analyser (Nieveen et al., 1998). Internal energy above the bog is calculated from slow response dry and wet bulb aspirated PT100 thermometers at 4 m height.

4. Results

4.1 The energy imbalance

The energy imbalance is shown in Fig. 2 as a function of wind direction for all half hour observations with $R_n > 100\,\mathrm{W\,m^{-2}}$. For most wind directions, the imbalance scatters around zero, except for western winds (direction around 270 degrees) where a positive imbalance dominates. Note, that a positive energy imbalance implies an overshoot of atmospheric heat fluxes as compared to the source strength. The wind directions with a dominance of positive energy imbalance (around 300°, or wind from south-west direction) correspond to the directions with the shortest distance, or fetch, to the forest edge (Fig. 3). Therefore, the measurements have been replotted as a function of fetch to the forest edge in Fig. 4, assuming that the wind direction over forest is constant during the half hour observation and independent of fetch (Kruijt, 1994; Hutjes, 1996). In Fig. 4, measurements have been averaged over 10 m fetch intervals to reduce the scatter. For fetches up to 400 m, an energy imbalance $I = 56\,\mathrm{W\,m^{-2}}$ with $\sigma = 21\,\mathrm{W\,m^{-2}}$ (uncertainty in the average value) is found, corresponding to 16% of the net radiation. At larger fetches, the budget was essentially closed ($I = 5\,\mathrm{W\,m^{-2}}$ with $\sigma = 37\,\mathrm{W\,m^{-2}}$ for fetches exceeding 400 m), although the measurements suggest a negative imbalance for fetches between 600 and 800 m. By presenting the sensitivity of the energy imbalance as a function of fetch to the forest edge, it is suggested that a limited fetch is the cause of the imbalance. The fetch of 400 m can be converted to a fetch to height ratio of 15, based on the measurement height or fetch to height ratio of 28 above the displacement height of 12.5 m.

The observation of an overshoot of atmospheric heat fluxes with short fetch is supported by measurements by Hutjes (1996, p 77), at a height of 26 m above a mixed-deciduous forest of 20–22 m height, adjacent to agricultural land. His results are reprinted in Fig. 5 with his affirmation. Hutjes found an overshoot of $\sim 40\,\mathrm{W\,m^{-2}}$ in the total turbulent heat fluxes at a fetch of less than 500 m, corresponding to 10% of the net radiation. The fetch of 500 m coincides with a fetch to height ratio of 19 (height above the ground) or 50 (height above the estimated displacement height). With increasing fetch, the ratio of total turbulent heat fluxes to net radiation approached unity. As the observations of these two, different measurement campaigns both show an

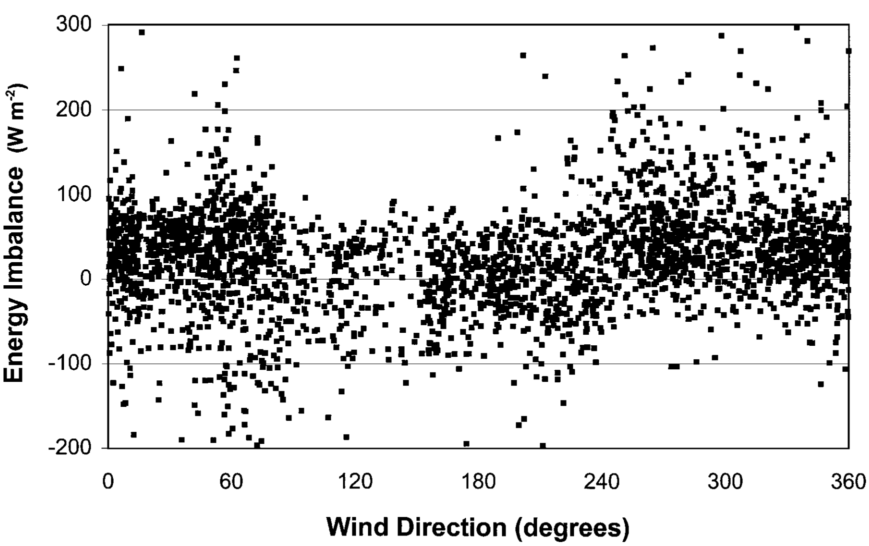


Fig. 2. Energy imbalance above forest against wind direction for $R_n > 100\,\mathrm{W\,m^{-2}}$

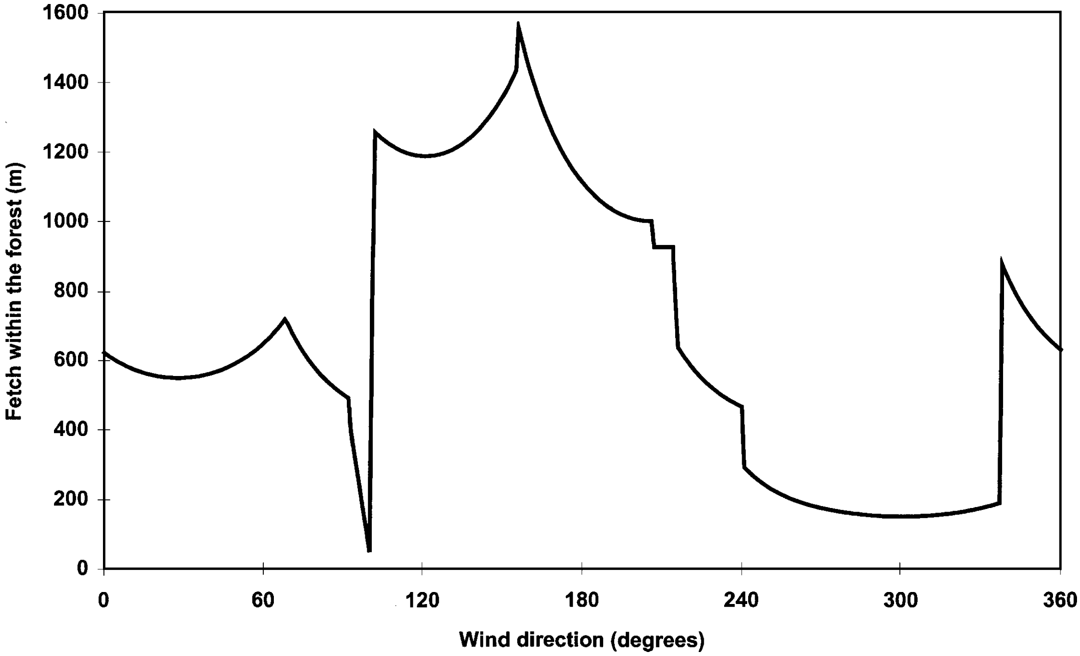


Fig. 3. Fetch, or distance to the forest edge, of the forest measurement tower as a function of wind direction

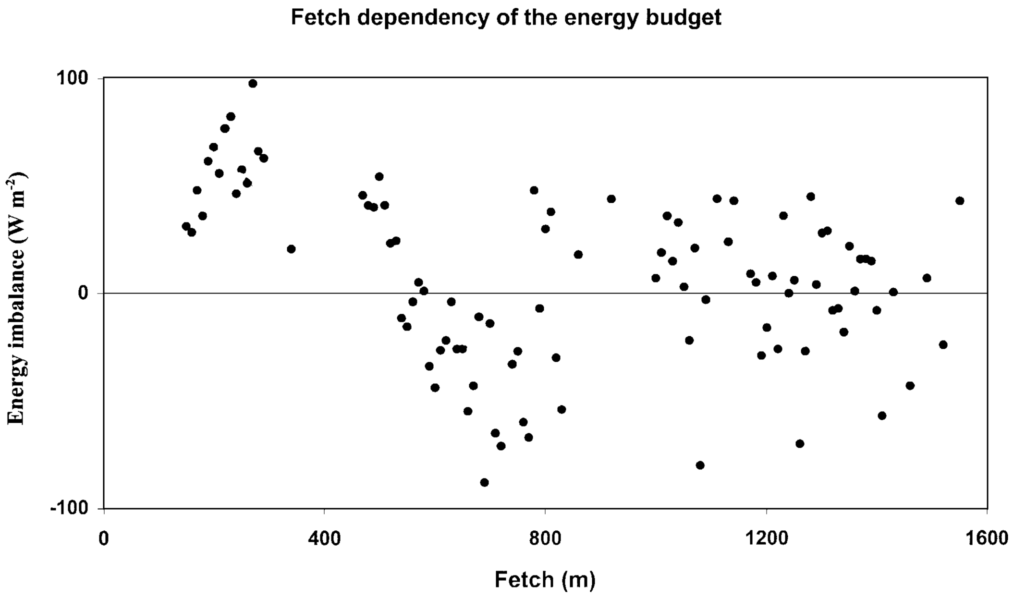


Fig. 4. Energy imbalance against fetch within the Bankenbosch forest. Every point is averaged over all measurements for $R_n > 100\,\mathrm{W\,m^{-2}}$ in succeeding 10 m fetch intervals

enhancement of heat fluxes with limited fetch, a process analyses is executed to explain the heat flux enhancement downwind of a forest edge.

4.2 Advection

The influence of advection on the energy imbalance is analysed by comparing the atmospheric temperature and humidity above the neighbouring sites. Measurements were selected on wind direction into the forest. Data for all values of net radiation were used to obtain a maximum range of differences in internal energy ($c = \rho c_p \theta + \lambda \rho_v$) between the air masses above the bog and the forest. Figure 6 shows an increase of the energy imbalance above forest with increasing difference

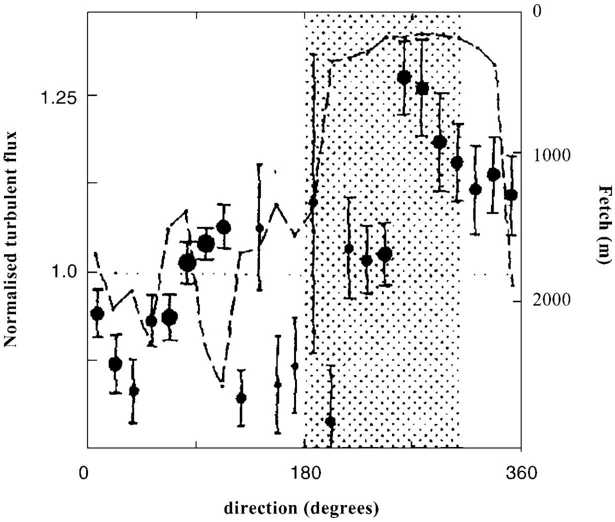


Fig. 5. Normalised turbulent heat fluxes $(H + \lambda E)/R_n$ against wind direction, measured in the Sleen forest by Hutjes (1996). The shading in the latter indicates upwind agricultural land, in other directions the upwind terrain is mixed forest of slightly lower height. Dot size relates to the number of observations in each class, and error bars to standard deviation

in internal energy, which is attributed to advection. Expect for this result and the large scatter in individual measurements, Fig. 6 shows two more interesting phenomena: 1) The energy imbalance tends to be positive for all differences in atmospheric heat, even when the air above the bog is cooler and/or dryer than above the forest, and 2) The difference in internal energy of the air above these neighbouring patches can be quite large: up to $30\,\mathrm{kJ\,m^{-3}}$. Such a large difference would require a temperature difference of 25°C, or a difference in water vapour density of $12\,\mathrm{g\,m^{-3}}$. For a better understanding of these phenomena, a more detailed analysis is made of the heat differences when the wind blows from the bog into the forest.

The temperatures at both sites are very similar although the air above the bog tends to be cooler at low temperatures as compared to the forest (Fig. 7a). The difference is explained by the aerodynamically smooth surface of the bog, resulting in enhanced vertical gradients at a given flux. By further assuming small horizontal gradients at the blending height, the enhanced gradients above the bog result in lower temperatures during the night as compared to the forest site. The temperature difference between both sites is most pronounced during the night when a stable atmospheric stratification above the bog enhances vertical gradients.

In contrast to the small difference in temperature, the difference in water vapour density between the neighbouring sites is quite large (Fig. 7b). The air above the bog is mostly more humid, the difference in water vapour density rises up to a factor two. This difference largely exceeds the accuracy of the sensors, which is estimated to be 5%. So, differences in internal

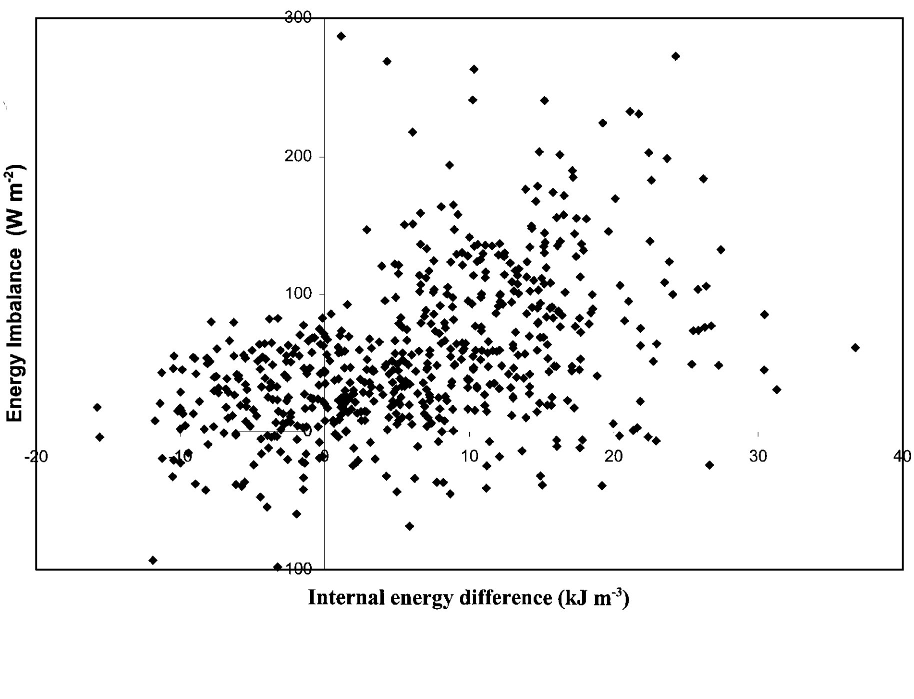
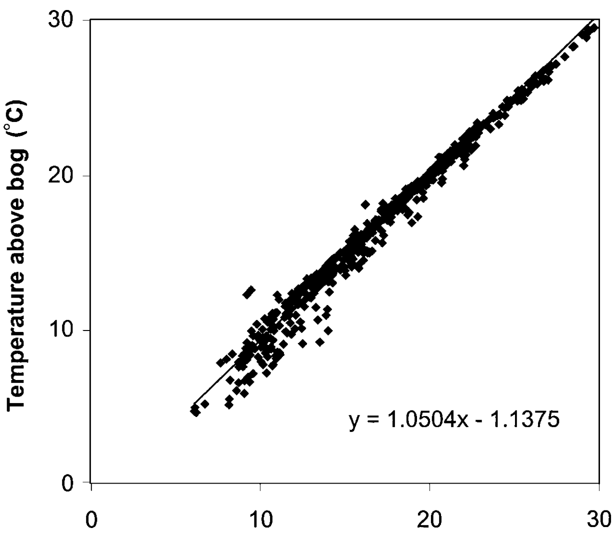


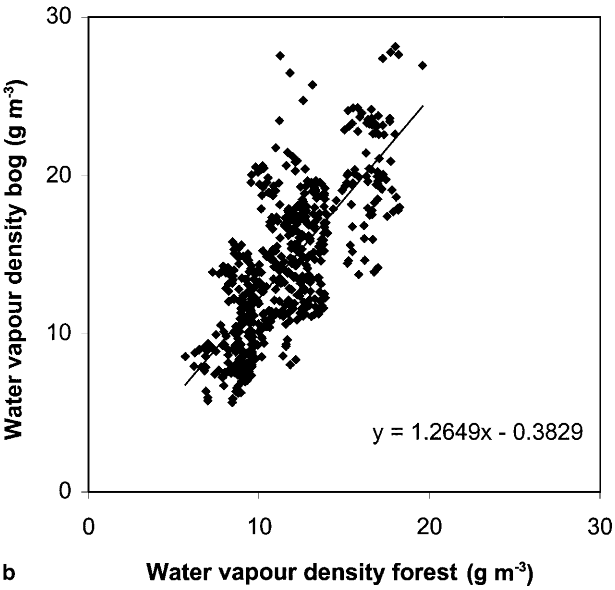
Fig. 6. Energy imbalance against the difference in heat between the air above the bog and the forest, for wind towards the forest (wind direction between 250° and 320°)

energy above these sites are primarily caused by differences in water vapour density.

The temperature and water vapour measurements are combined to the internal energy in Fig. 7c. Note that the heat density is related to the temperature in °C. Figure 7c shows that the internal energy above bog increases more than proportional with the internal energy above forest. The standard error of estimate of the linear fit in Fig. 7c ($5.0\,\mathrm{kJ\,m^{-3}}$) is smaller than in Fig. 7b ($3.2\,\mathrm{g\,m^{-3}}$, equivalent to $7.9\,\mathrm{kJ\,m^{-3}}$), meaning that extreme humidity differences are compensated by temperature differences. With compensation we mean here that an extremely large difference in humidity between the air above the bog and the forest tends to go with a temperature difference of opposite sign.

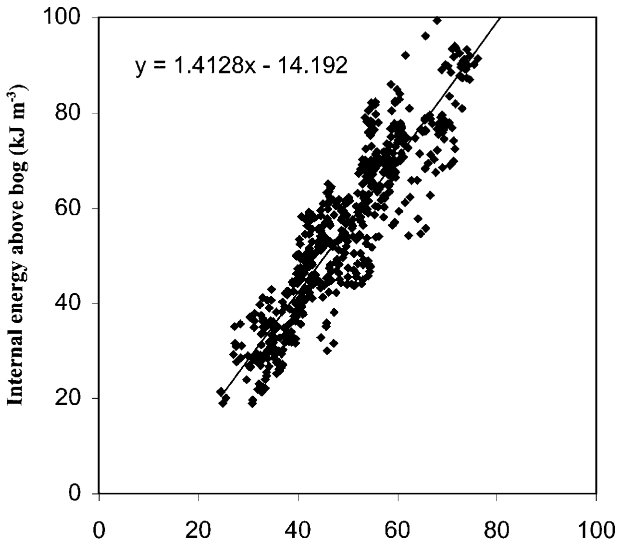


a



b

Fig. 7. A comparison of temperature (**a**), water vapour density (**b**), and internal energy (**c**) of the air above the bog and the forest for wind towards the forest, including linear regression lines



c

Fig. 7 (*continued*)

Figure 8 shows that the difference in internal energy is related to the net radiation above forest. Radiation energy is used to increase the internal energy of the air. The impact of the input of energy on the internal energy of the air is most strongly above the bog where the turbulence level is lower and the energy input is more slowly transported to larger heights. Figure 8 shows that the difference in internal energy increases in a non-linear way with net radiation. The non-linearity is explained by the atmospheric stability above the bog: with increasing net radiation, the surface layer becomes more unstable, so the turbulence level increases and the energy input can spread more quickly.

4.3 Upwind surface fluxes

The relatively high internal energy of the air above the bog might be caused by high surface heat fluxes. This hypothesis was checked by comparing the fluxes at the forest and bog sites. The surface heat fluxes are approximated by the net radiation. The net radiation of the bog is only 77% of the value above the forest (Fig. 9). This is

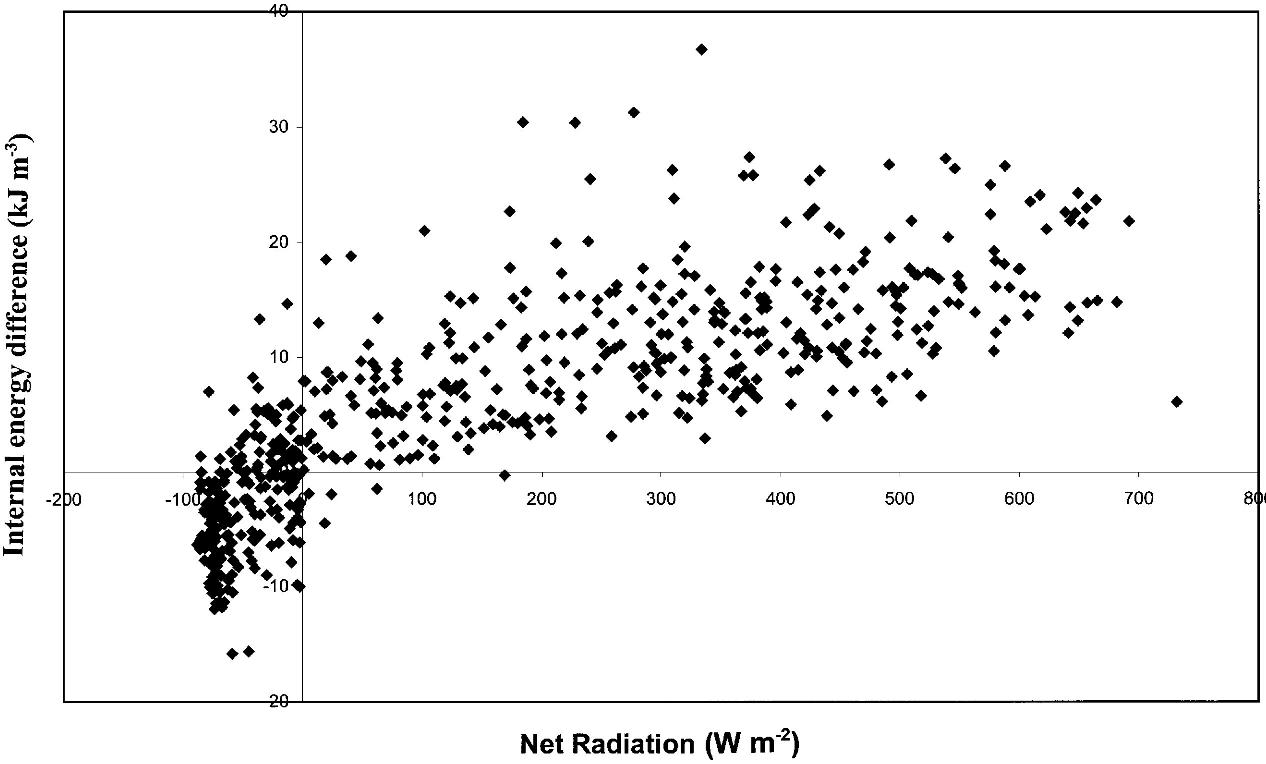


Fig. 8. The difference in internal energy of the air above the bog and the forest as a function of the net radiation above forest

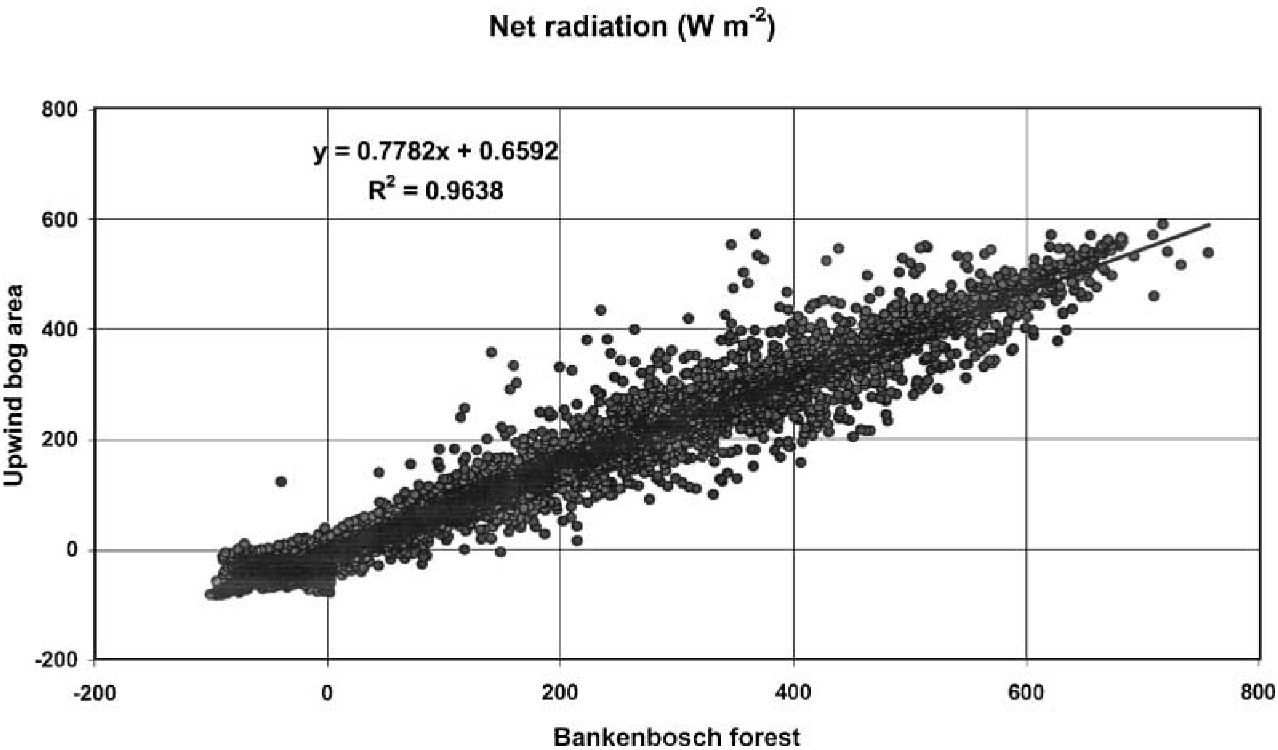


Fig. 9. Net radiation from the Fochteloër bog versus the value from the adjacent Bankenbosch forest. Data are from June 1995

caused by the relatively high albedo of the bog (0.16 versus 0.10 of the forest, van Breugel et al., 1999b; Nieveen et al., 1998) and the relatively high surface temperature of the bog. The higher surface temperature is associated with the low aerodynamic roughness length of the bog. Net radiation is only a proxy for the atmospheric surface fluxes above bog as soil heat flux could not be determined accurately at this site with many small open water patches. Therefore, a second test is made.

An alternative estimate of the difference in surface fluxes arises from the atmospheric measurements. The sensible heat flux above the adjacent bog is on average 62% of the same flux above the forest (Fig. 10a). A comparison of latent heat fluxes at both sites, measured at the same heights as for sensible heat fluxes, shows an average percentage of 66% (Fig. 10b). These results were obtained for wind directions into the forest to obtain measurements at the bog that are unaffected by advection. So, even when the forest surface fluxes are corrected for advection (a correction of 16% would be reasonable), the measurements indicate lower surface fluxes at the bog site. The lower surface fluxes at the bog site imply that the observed spatial differences in internal energy are not caused by different surface energy fluxes.

Figures 9, 10a and 10b also show that negative energy fluxes above forest, which mostly occur at night, are strongly enhanced as compared to the value above the bog. This is attributed to the development of a nocturnal stable atmospheric layer above the bog which limits the energy fluxes at this site. This stability effect is less pronounced at the aerodynamically rough forest site.

4.4 Energy and momentum fluxes

The energy imbalance is compared to the imbalance of momentum flux. The imbalance of momentum flux is characterized by u^*/u, the ratio between friction velocity and wind velocity. As the influence of stability just above forest is small, this parameter primarily shows whether atmospheric diffusion is smaller or higher than expected. The analysis is restricted to $R_n > 100\,\mathrm{W\,m^{-2}}$ and for wind directions into (Fig. 11a) and out of the forest (Fig. 11b).

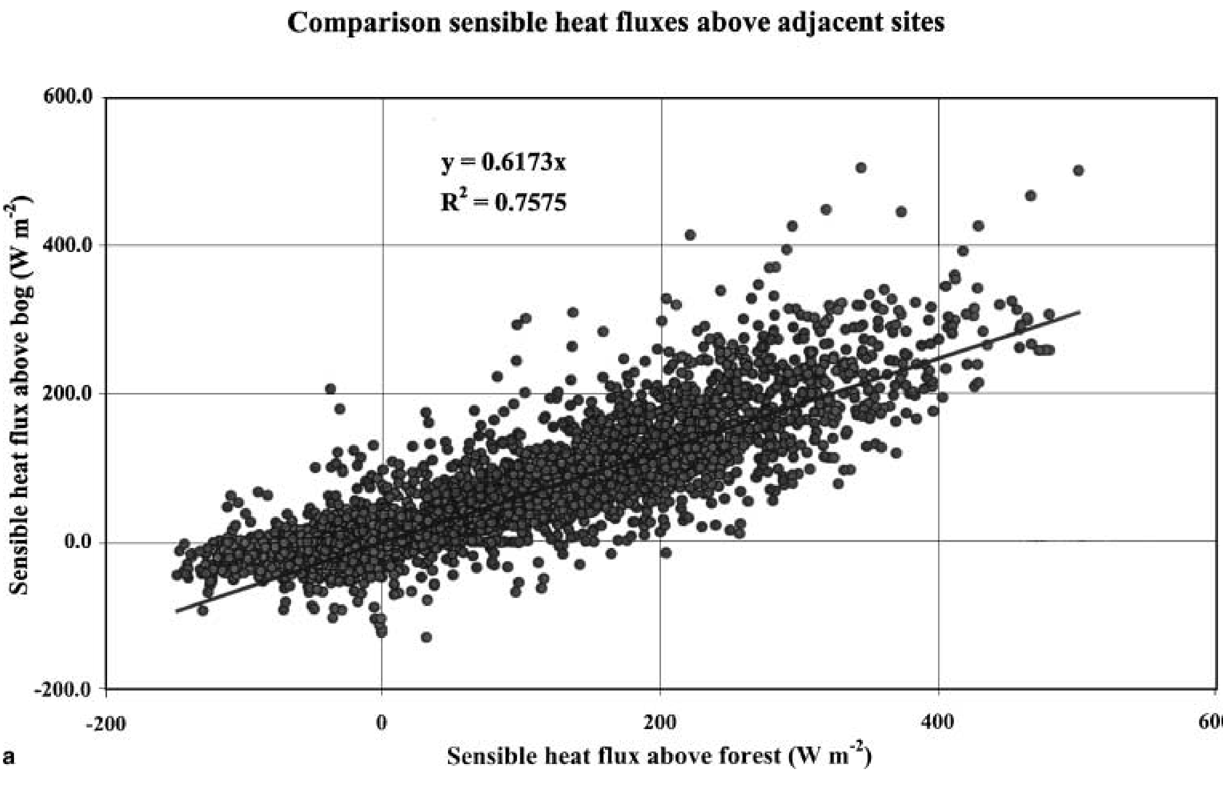


Fig. 10. Sensible (**a**) and latent (**b**) heat flux from the Fochteloër bog versus the value from the adjacent Bankenbosch forest. Data are from June 1995

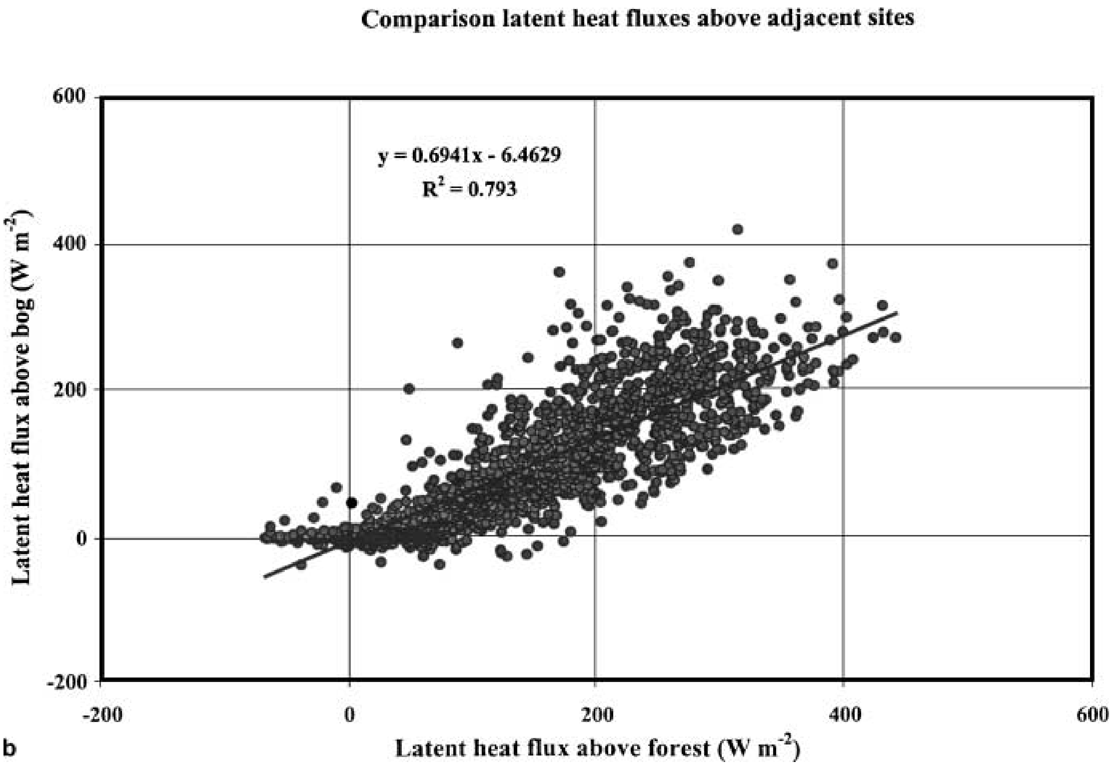


Fig. 10 (*continued*)

The figure for wind out of the forest is interpreted as characteristic for undisturbed flow over forest. For both wind directions, u^*/u ranges between 0.05 and 0.40 with a standard deviation of 0.06. On average: $u^*/u = 0.19$ for wind into the forest and 0.18 for wind with a long fetch over forest. The energy imbalance for wind directions into and out of the forest is on average 30, respectively $-6\,\mathrm{W\,m^{-2}}$. The difference in energy imbalance between these classes is thus $36\,\mathrm{W\,m^{-2}}$. This is less than the $56\,\mathrm{W\,m^{-2}}$ imbalance, found for fetches less than 400 m (Fig. 4), due to different selection criteria for wind direction and fetch.

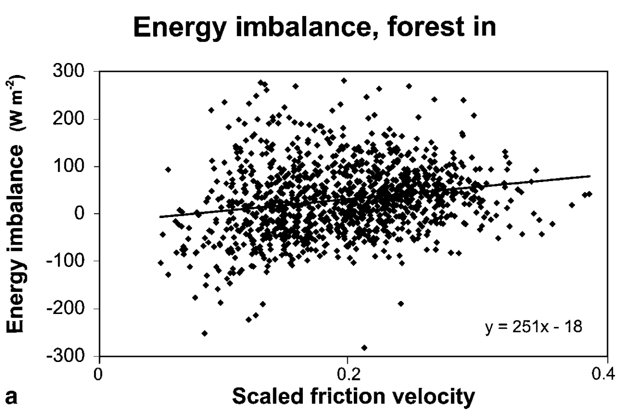


Fig. 11. Energy imbalance against the scaled friction velocity u^*/u for (**a**) wind directions between 220° and 360° (direction towards the forest), and (**b**) wind directions between 0° and 220° (direction out of the forest)

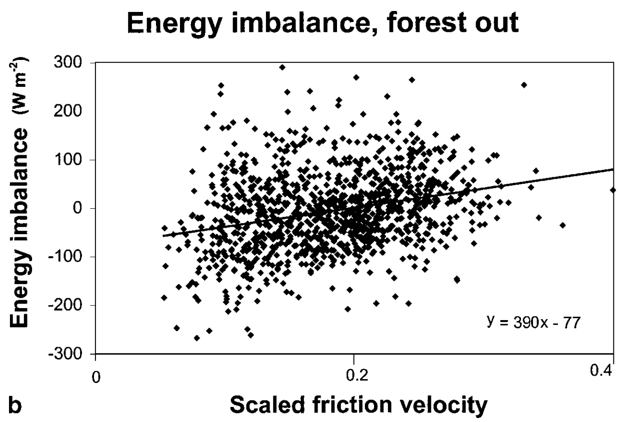


Fig. 11 (*continued*)

The small sensitivity of u^*/u to wind direction is in agreement with observations by Gash (1986), Kruijt (1994), Irvine et al. (1997), Gardiner and Hill (1997) and van Breugel et al. (1999a), which show a quick adjustment of u^*/u to the new surface downwind of a forest edge. This adjustment occurs with a fetch/height ratio between 16 and 30 (Gash, 1986; Kruijt, 1994), where the height is related to the height above the zero-plane displacement. Converted to the Bankenbosch site, this would lead to a fetch of 220 up to 300 m to reach equilibrium at measurement height, as compared to 400 m for the energy fluxes.

Figure 11 shows that the energy imbalance is related to deviations in u^*/u, in agreement with Lee (1998). The large scatter in Fig. 11 prevents a conclusion on the precise relation between the energy imbalance and u^*/u. Therefore, the most simple (linear) relation is assumed. The linear fit on the data for wind out of the forest results in $\partial I/\partial(u^*/u) = 390\,\mathrm{W\,m^{-2}}$. So, the average difference in u^*/u for wind into and out of the forest of 0.01 corresponds to an energy imbalance of only $4\,\mathrm{W\,m^{-2}}$. As the observed imbalance of energy fluxes (36–$56\,\mathrm{W\,m^{-2}}$) exceeds the imbalance that would arise from unadjusted momentum fluxes ($4\,\mathrm{W\,m^{-2}}$) by an order of magnitude, disrupted local diffusion cannot be considered as a major cause of the energy imbalance.

5. Discussion

The measurements show a significant energy imbalance above forest downwind of an edge. The energy imbalance appears to extend to larger fetches than the disruption of the momentum flux. Because of the imbalance, atmospheric heat flux measurements near forest edges are not representative for the underlying surface. In this chapter we will discuss and try to explain these observations.

5.1 Measurements

The study points to a fetch dependent energy imbalance. In order to check whether this results is caused by measurement errors, it is sufficient to focus the analysis on errors which are dependent on fetch or wind direction. Three possible fetch dependent errors are checked: vertical wind, local variability and scatter.

The vertical wind speed is expected to depend on fetch, but this does not affect the results as the flux measurements were carefully corrected for vertical wind. Wind direction dependent errors cannot be excluded as the measurements were taken in the roughness sublayer and individual roughness elements may influence the results. However, as the two independent field campaigns of the present study and Hutjes (1996) support each other in the observation of enhanced heat fluxes at fetches less than 400–500 m, it is rather unlikely that the overshoot of fluxes was caused by local surface variability in the roughness layer. The energy imbalance measurements show a large scatter, which is primarily attributed to the stochastic measurement error in atmospheric heat fluxes. Also, fluctuations in heat storage below measurement level influence the scatter in the energy imbalance. Allthough the scatter reduces the accuracy of the result, it cannot explain the significant enhancement of heat fluxes at short fetches.

The measurements of Hutjes qualitatively show the same effect; quantitatively they show a smaller heat flux enhancement at larger fetches than observed at the Bankenbosch site, suggesting that his measurements were executed beyond the fetches where the strongest enhancement occurs. Another possibility for the difference is the forest density. The present study was executed above a heavily thinned forest (LAI = 1.8) and the study of Hutjes was executed above a moderately dense forest with LAI = 5.5. Further study is recommended to analyse the influence of forest density on heat flux enhancement.

The internal energy is measured at a single height below the flux measurements. In order to measure advection, equation 4 states that the internal energy should integrated from the surface to the flux measurement height. Thus, single level measurements are only a proxy for advection. It is recommended to execute profile measurements to quantify advection.

5.2 Advection and upwind surface fluxes

The study points to a confrontation between different methods to estimate advection. Advection of heat can be estimated from the difference in surface heat fluxes in the upwind direction, the so-called ‘footprint area’ in case of a horizontally constant diffusivity. In the more complex case that the diffusivity varies as well, information of the surface heat fluxes is not enough to quantify the advection (Wilson et al., 2001) and information on the flow disruption is needed as well.

The relatively high internal energy of the upwind air mass during daytime is not caused by high surface heat fluxes of the upwind bog as the measurements indicate that the surface heat fluxes of the bog are relatively small. Instead, the high internal energy of the advected air is explained by the low aerodynamic roughness of the upwind bog, leading to restricted diffusivity and accumulation of internal energy near the surface of the bog. So, supplementary energy, downwind of the forest edge, may well be advected from an area with a shortage of surface energy fluxes due to accumulation of internal energy below the measurement level of the upstream area.

The argumentation implies that footprint models should not be used straightforwardly to calculate scalar fluxes after a change in surface roughness but need to be extended with an estimate of flux modification by variability of turbulence level in the upwind direction.

5.3 Adjustment rates for momentum and scalar fluxes

The experimental result, that the local friction velocity adjusts more quickly to the forest than the heat fluxes points to an important difference in the transport mechanisms of momentum and heat near a forest edge. The difference can be understood as part of the momentum is absorbed by pressure gradients around the forest edge (Nieveen et al., 2001), a mechanism which does not directly affect the heat transport (Klaassen and Claussen, 1995). So, heat is redistributed more slowly and a longer fetch is needed for the heat fluxes to adjust to the underlying forest. As the fluxes of other scalars, like carbon dioxyde, are also not directly affected by pressure gradients, this analysis suggests that all scalar fluxes adjust slowly as compared to momentum fluxes to equilibrium downwind of a forest edge. In this experiment, adjustment of energy is found after a fetch of 400 m and adjustment of momentum is estimated after 220–300 m, suggesting that the fetch to reach equilibrium downwind of a forest edge is increased by a factor 1.5 for scalar fluxes as compared to momentum fluxes.

6. Conclusions

The atmospheric heat fluxes downwind of a forest edge exceed the surface fluxes from the underlying forest. The possibility of a measurement error is not likely, as the overshoot was observed in two different campaigns. The local overshoot of fluxes within 400 m downwind of a forest edge is $56 \pm 21\,\mathrm{W\,m^{-2}}$, equal to 16% of the net radiation in the present study. The enhancement is attributed to advection of internal energy of the air, meaning that relatively warm and moist air enters the forest patch. In the present experiment, advection of energy is dominated by latent heat advection.

An energy imbalance may arise when the surface heat fluxes deviate from the upwind area but also when the turbulent diffusivity varies in the wind direction. Surface heat flux differences cannot explain the imbalance as the sign of this effect is opposite to the observed imbalance. It is concluded that a straightforward use of a source area model is not useful to calculate vertical gradients of scalar fluxes downwind of a roughness transition. Instead, a source area model must be combined with an estimation of the flux modification by disrupted diffusivity, to estimate atmospheric fluxes downstream of a forest edge.

Local turbulence (u^*/u) is only slightly increased at the measurement location downwind of the forest edge. As a result, the direct impact of the local enhancement of diffusion on the energy imbalance is small, up to $4\,\mathrm{W\,m^{-2}}$. This mechanism is of secondary importance only to explain the observed heat flux overshoot. Differences in the rate of adjustment of scalar fluxes as compared to momentum fluxes are attributed to pressure gradients around the forest edge which absorb momentum without interfering scalars. So, special care is needed when atmospheric fluxes of heat, or other scalars, are used to estimate the fluxes from an underlying surface with upwind heterogeneities. When the quality of atmospheric measurements with respect to the underlying surface is estimated from fetch to height ratios, it is provisionally recommended to increase this ratio by a factor 1.5 for scalar fluxes.

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